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Semi-natural areas of Tarim Basin in northwest China: Linkage to desertification



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HIGHLIGHTS

GRAPHICAL ABSTRACT

- An approach for mapping semi-natural land was developed with multi-source datasets.
- Spatio-temporal changes of semi-natural land were investigated in Tarim Basin.
- Substantial loss of semi-natural land in Tarim Basin from 1990 to 2010.
- The linkage between semi-natural land and desertification was demonstrated.
- Policy implication was proposed for both land resource and environment management.

A R T I C L E I N F O

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ABSTRACT

Semi-natural lands are not intensively managed lands, which have ecological significance in protecting artificial oasis and preventing desertification in arid regions. The significant shrinkage and degradation of semi-natural lands in the land-use intensification process have caused severe desertification. However, there is a knowledge gap regarding the spatio-temporal pattern and detailed classification of semi-natural lands and its quantitative relationship with desertification. Taking the Tarim Basin as an example, we proposed a comprehensive classification system to identify semi-natural lands for 1990, 2000, and 2010, respectively, using multi-source datasets at large scales. Spatio-temporal changes of semi-natural lands were then characterized by map comparisons at decade intervals. Finally, statistical relationships between semi-natural lands and desertification were explored based on 241 watersheds. The area of semi-natural lands in Tarim Basin was 10.77×10^4 km² in 2010, and desert-vegetation type, native-oasis type, artificial-oasis type, saline type and wetland type accounted for 59.59%, 14.65%, 11.25%, 9.63% and 4.88% of the total area, respectively. A rapid loss of semi-natural lands (9769.05 km²) was demonstrated from 1990 to 2010. In the fragile watersheds, the semi-natural lands were mainly converted to desert; while in the watersheds with advanced oasis agriculture, artificial-oasis type reclaimed to arable land was the major change. The occurrence of desertification was closely related to the type, area proportion and combination patterns of semi-natural lands. Desertification was prone to occur in regions abundant in desert-vegetation type and saline type, while less serious desertification was observed in regions with high proportion of artificial-oasis type and wetland type. Policy intervention and reasonable water

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resource allocation were encouraged to prevent the substantial loss of semi-natural lands, especially for the water-limiting watersheds and periods.

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1. Introduction

1.1. Semi-natural areas in arid region

Semi-natural ecosystem provides fundamental life-support services for human well-being and survival. Anthropogenic activities strongly converting semi-natural land to human-modified landscapes (Foley et al., 2005; Theobald, 2014) have brought profound environmental consequences such as land degradation and biodiversity loss (Halada et al., 2008), which is even more serious in the vulnerable arid area. The spatio-temporal changes of semi-natural lands are of great importance for making policy and maintaining ecosystem functions during landuse intensification process for sustainable landscape management and development (Dale et al., 2000; Proulx and Fahrig, 2010).

In our study, semi-natural lands are defined as the land resources without permanent and intensive use by human and can return to naturalness free of human influences. Land use types are divided to four categories according to different influence degrees of human activities (Di et al., 2015: Liu et al., 2005a.b): artificial land, semi-artificial land, semi-natural land and natural land. Semi-natural land includes forest, grassland and water body. Specific to arid region, desert riparian, occurring as narrow bands along a river or as small patches of wetland can stabilize vulnerable ecosystems (Cao et al., 2012; Ma et al., 1997) through preventing strong wind and encroachment of sand dunes and providing food and habitats for wildlife diversity (Yang et al., 2006). Desert-oasis ecotone with sparse desert vegetation is important for oasis ecological security and maintaining oasis internal stabilization (Li et al., 2014; Wang et al., 2007). With linear planting of trees/shrubs, field windbreaks are designed to reduce wind speed to protect adjacent crops from wind damage.

Unfortunately, accurate information regarding the spatial location, dynamics and detailed classification of these semi-natural landscapes at large scale are limited. To our knowledge, previous studies mainly focused on the spatial dynamics of semi-natural lands during urbanization and agricultural intensification process, without detailed consideration of semi-natural land types. García-Feced et al. (2015) developed the first map of semi-natural vegetation in agricultural land in European. European Environment Agency (2015) demonstrated that the loss of natural/semi-natural lands was mainly due to the spread of artificial and agricultural areas. Furthermore, studies on semi-natural land used the land cover classification system without consideration of detailed ecological function. Zhou (2008) performed trajectory analysis of natural/semi-natural land covers using classification systems including grass, woodland, salty grass, water body and bare ground. Specific semi-natural land types were studied such as riparian forest (Ling et al., 2015; Liu et al., 2012; Hao and Li, 2010; Xu et al., 2007), sparse vegetation in desert-oasis ecotone (Amuti and Luo, 2014; Chu et al., 2014; Wang and Li, 2013; Wang et al., 2015; Zhao and Chang, 2014), and sparse vegetation in extreme vulnerable area (Chen et al., 2010; Xu et al., 2007; Yu et al., 2012). However, the types of semi-natural lands in arid region are far more than these types. So far, no map has been available for documenting the spatio-temporal patterns of semi-natural land resources with detailed classifications at large scales in arid region.

1.2. Desertification in arid region

Desertification is one of the greatest environmental challenges in arid regions (Varghese and Singh, 2016). Inherently harsh physical conditions and climate changes such as global warming and aridification make the ecosystem fragile and prone to desertification (Chen and Tang, 2005; Marland et al., 2003; Zhou et al., 2009). However, anthropogenic activities such as over exploitation of natural resources, overgrazing, and firewood gathering are demonstrated to bring in faster and more severe desertification (Chen and Tang, 2005; Feng et al., 2015). Man-made disturbances of vegetation cover are the important direct reasons for desertification (Liu et al., 2004; Tao, 2014) owning to extensive loss of semi-natural lands (forest and grassland) for urban sprawl, overgrazing and crop production (Amuti and Luo, 2014; Feng et al., 2015). Additionally, the limited water resource is firstly allocated to agricultural lands and human development, indirectly leading to the degradation and loss of natural vegetation (Fan et al., 2002; Liu et al., 2013; Luk, 1983).

Without any available maps of the spatial pattern of semi-natural lands, the effect of semi-natural lands on the desertification was limited addressed on specific semi-natural land types based on qualitative methods (Cheng, 2007; Ci and Yang, 2005; Song et al., 2000). Therefore, further quantitative analysis between semi-natural lands and desertification is warranted for landscape planning to prevent desertification process.

1.3. Tarim Basin: an overview

Located in the south of Xinjiang, northwest China, Tarim Basin is China's largest inland basin, surrounded by Tian Shan to the north and Kunlun Mountains to the south. The Taklimakan Desert, the world's second largest shifting sand desert, is located in the center of the basin. Many oases of different sizes and shapes are interspersed in such large deserts (Su et al., 2007). The climate is extremely dry, and the annual rainfall is less than 50 mm (Tao et al., 2008). Vegetation cover consists of drought tolerant trees and shrubs along the rivers (Liu et al., 2013). The Tarim River is the major water source for the natural ecosystems, agriculture, and settlements and industry (Thevs, 2011). According to China's water resource zone map, there are ten watersheds (Fig. 1), namely Aksu River Basin (A), Yarkant River Basin (B), Weigan River Basin (C), Kashgar River Basin (D), Hotan River Basin (E), Kaidu-Kongque River Basin (F), mainstream of Tarim River (G), Qarqan River Basin (H), Keriya River Basin (I), and Taklimakan Desert (J).

Tarim Basin has experienced significant shrink and degradation of natural/semi-natural lands as a result of intensive human activities since the 1960s (Chen et al., 2011; Xu et al., 2008). From 1949 to the late 1980s, the area of irrigated oases increased from 1.3×10^4 km² to 5.87×10^4 km² and caused a sharp decline in oasis peripheral vegetation (Chen, 2014). As the dominant type along the riparian corridor, *Populus euphratica* has shrunk considerably in area over the past 50 years (Peng et al., 2014). Oasis-desert ecotone decreased remarkably and resulted in the Kuruk Desert moving 60 km toward the valley (Jiang et al., 2003). To restore the degraded ecosystem in Tarim Basin, the ecological water conveyance project has been implemented since 2000 through artificial water-transfer to the lower river (Ye et al., 2009a). The spatial pattern and dynamics of semi-natural land before and after the implementation of the project are worth paying attention to and further being investigated.

1.4. The aims of our study

In this study, taking Tarim Basin as an example, we proposed a seminatural land classification system and a new method to map different types of semi-natural land for 1990, 2000, and 2010, respectively, through a combination of multi-source datasets. Spatial pattern and dynamics of semi-natural land were characterized during the periods of 1990–2000 and 2000–2010 (before and after the implementation of the ecological restoration project). Then, we took time series AVHRR NDVI to monitor desertification and explored the relationship between semi-natural land and desertification in these two periods. This study will provide a detailed spatio-temporal distribution analysis of seminatural land and its relationships to desertification, which is of prime importance to support the policy decision for sustainable land use planning and management.

2. Methods and materials

2.1. Data description

1) Land use and cover data. The 1:100,000 land use and cover data of Tarim basin in 1990, 2000 and 2010 from China's National Land-Use/ Cover Dataset (NLCD) was obtained from the Data Center for Resource and Environmental Sciences of the Chinese Academy of Sciences (http://www.resdc.cn/). This dataset is derived from the visual interpretation of Landsat TM/ETM + images in the late 1980s, 1999/2000, and 2009/2010, respectively, and its accuracy is validated through extensive field survey datasets (Liu et al., 2014; Zhang et al., 2014). There are six types (cropland, forest, grassland, water bodies, built-up land and unused land) and 25 subtypes of land cover. 2) Normalized Difference Vegetation Index (NDVI) product. Time series AVHRR GIMMS 3g NDVI data from January 1990 to December 2010 with a spatial resolution of 1/12 degree and a 15-day interval (Fensholt and Proud, 2012) was used to calculate the vegetation fraction cover for mapping semi-natural land classification and perform land desertification monitoring. The maximum value composite method was used to generate monthly NDVI.

3) Digital Elevation Model (DEM). Elevation data is available from the Shuttle Radar Topography Mission (SRTM) at the 90 m spatial resolution (http://www2.jpl.nasa.gov/srtm/cbanddataproducts.html). In this study, 241 sub watersheds were obtained from the further segmentation of those nine watersheds based on the DEM dataset using ArcGIS Hydro Tools (v2.0, Djokic et al., 2011).

4) Geomorphological Map. Geomorphic classification from the 1:1,000,000 Geomorphological Map of China (Li et al., 2009) acquired from the Data Sharing Infrastructure of Earth System Science of China (http://www.geodata.cn/) was used to extract semi-natural land in lowland.

2.2. Classification system and mapping algorithm of semi-natural land

2.2.1. Classification system for semi-natural land

An ideal classification system should be applicable over extensive areas, containing hierarchical classes that would allow aggregation of categories, resulting in repeatable and consistent results and comprehensive classes covering all areas (Anderson et al. 1976; Theobald,



Fig. 1. The sketch map of study area and spatial location of ground reference data in Tarim Basin (a). The pictures (b) taken in 2010 show semi-natural lands in Tarim Basin. Aksu River Basin (A), Yarkant River Basin (B), Weigan River Basin (C), Kashgar River Basin (D), Hotan River Basin (E), Kaidu-Kongque River Basin (F), mainstream of Tarim River (G), Qarqan River Basin (H), Keriya River Basin (I), and Taklimakan Desert (J).

b



Fig. 1 (continued).

2014). Adhering to these criteria, a two-level hierarchical classification system of semi-natural land is proposed (Table 1). The first level includes artificial-oasis type, native-oasis type, wetland type, desert-vegetation type and saline type according to various ecological functions.

Artificial-oasis type has three subclasses, i.e., artificial-oasis forest, artificial-oasis grassland and reservoir. It will reduce wind speed, improve the oasis interior habitat conditions and regulate water resource. Native-oasis type includes native-oasis forest and native-oasis grassland. It is dominated by zonal vegetation relying on groundwater and receives little influence from human activities. It is mainly distributed in valleys, rivers, lakes, groundwater spilling belts at the front of piedmont alluvial plains and low-lying alluvial land adjacent to a river. Native-oasis type provides extensive ecological services for biological diversity protection and water conservation, preventing strong wind and encroachment of sand dunes and protecting artificial oases. Wetland type refers to the water bodies and transitional zones between land and water (i.e., wetlands). It provides water resource for agricultural oasis and habitats for biodiversity conservation. Desert-vegetation type primarily refers to vegetation community located in desert-oasis ecotone and desert. With sparse desert vegetation, desert-vegetation type could control active sand dunes, slow down the sand dunes moving to oases, and prevent desertification expansion, which is important for oasis ecological security and maintaining oasis internal stabilization. According to distance away from artificial oases, desertvegetation type is divided into ecotone type and desert type. Saline type refers to the saline land for dry drainage, which effectively accommodates higher concentration of alkali discharged by farmland ecosystems and alleviates salinization threat to the stability of oasis ecosystems (Hamid et al., 2002; Shi et al., 2004).

2.2.2. Algorithm for mapping semi-natural lands

Based on the semi-natural land classification system, a hierarchical classification procedure was developed to identify these areas (Fig. 2).

Four major ecological zones (artificial oasis, natural oasis, desertoasis ecotone and desert) in Tarim Basin were firstly identified, based on land cover types and the fraction vegetation cover calculated from AVHRR GIMMS 3g NDVI (Carlson and Ripley, 1997). The detailed criteria for these four major zones were as follows (Wang et al., 2004). 1) Artificial oasis: irrigation area including forestry and grassland with fraction vegetation cover over 30%, reservoir and pond water, settlements, and traffic construction land. 2) Natural oasis: forest and grassland outside of artificial oasis with fraction vegetation cover over 30%, lake and

 Table 1

 A hierarchical semi-natural land classification system.

Level I	Level II	Description	
Artificial-oasis type	Artificial-oasis forest	Artificial-oasis forest refers to the forest within or at the edge of artificial oasis, Its function is mainly about reducing wind speed improving the oasis interior habitat conditions and protecting the crop growth.	
	Artificial-oasis grassland	Artificial-oasis grassland is within the artificial oasis. It is improving interior condition of the artificial oasis and maintaining the urban ecological balance	
	Reservoir	Reservoir is built for protecting biological diversity, fighting flood, water purification and adjusting local microclimate.	
Native-oasis type	Native-oasis forest Native-oasis grassland	It is natural protection shield for the ecological system in the arid region. Its main function is wind prevention, sand fixation and soil improvement	
Wetland type	Water bodies	Its main function is water resource provision for agricultural oasis and biodiversity conservation.	
	Wetlands	Including lands between normal water level and flood level, land with a permanent mixture of water and herbaceous or woody vegetation. Its main function is biodiversity conservation.	
Desert-vegetation type	Ecotone type	Vegetation community in desert-oasis ecotone, its main function is wind prevention and spand fixation	
	Desert type	Vegetation community in desert, its main function is dunes fixation and reduction of sources of dust storms.	
Saline type	Saline land for dry drainage	The uncultivated land mixed in farmland and lowland at edge of oasis. Its main function is to accommodate higher concentration of alkali discharged by farmland ecosystems.	

river water. 3) Desert-oasis ecotone: natural vegetation with fraction vegetation cover between 5% and 30%. 4) Desert: land with fraction vegetation cover less than 5%, including desert, saline alkali land, bare land and gravel desert.

Then we classified those four major ecological zones into five types, including artificial-oasis type, native-oasis type, wetland type, desertvegetation type and saline type distinguished based on ecological functions. Specifically, both native-oasis type and wetland type were in the natural oasis but with different ecological functions and land covers. Forest and grassland in natural oases were identified as the nativeoasis type, whereas water bodies and swampland were classified as the wetland type. Desert-vegetation type was distributed in desertoasis ecotone with land covers of grassland and forest. Saline type referred to saline land mainly distributed in lowland around artificial oases.

Semi-natural land types were further subdivided into 10 classes based on land cover, geomorphic condition and spatial distance. Specifically, according to land cover, native-oasis type was divided into native-oasis forest and native-oasis grassland. The subtypes within wetland type and artificial-oasis type differentiated the primary land covers. Desert-vegetation type was further categorized to ecotone type and desert type, according to the vegetation's distance to oasis.

2.2.3. Ground truth samples for the accuracy assessment of semi-natural land maps

To assess the accuracy of the semi-natural land maps in Tarim Basin, we conducted extensive field surveys of land cover types with local researchers in the middle and upper reaches of Tarim Basin from July to August 2010 and in lower reaches of Tarim Basin in September 2013, respectively (Fig. 1). We collected 813 ground truth samples with GPS information, including 663 ground truth samples in the middle and upper reaches of Tarim Basin and 150 geo-referenced photos in the lower reaches of Tarim Basin. The land cover types of validation data were grouped into two categories, semi-natural land and non-semi-natural land.

2.3. Land desertification monitoring based on trend analysis of NDVI coefficient of variation

Serious desertification ultimately results in long lasting and observable loss of vegetation cover and productivity over time and space (Helldén and Tottrup, 2008). Therefore, vegetation degradation is an effective indicator for land desertification identification. NDVI in arid and semi-arid regions has been demonstrated highly correlated with such biophysical variables as leaf area index (LAI), biomass and vegetation cover (Carlson and Ripley, 1997; Fan et al., 2008; Jin et al., 2014). The coefficient of variation (CV) of the NDVI values can identify changes in vegetation growth cycles, which have been successfully applied for desertification monitoring in arid regions (Liu et al., 2003; Milich and Weiss, 2000). In this study annual pixel-level NDVI CV was calculated from monthly NDVI values. The Mann-Kendall test, a non-parametric trend analysis method, was used to determine the trend in pixel-level CV values over the study period. The slope of this trend was quantified by Theil-Sen's median slope method (Sen, 1968; Theil, 1950). The slope of CV was divided into six levels according to the frequency histogram of pixel numbers with CV values to indicate different desertification levels (Table 2).



Fig. 2. Workflow of semi-natural land mapping in Tarim Basin.

Table 2

Desertification levels	Strong desertification	Moderate desertification	Light desertification	Non-desertification		
Thresholds	<-0.010	-0.010-0.005	0.005–0	>0		

2.4. Relationship between semi-natural land and desertification

In Tarim Basin, soil wind erosion is one of the biggest threats to the sustainability of ecosystems, and vegetation cover can slow down the speed or restore the degrading ecosystems. Investigating the relationship between semi-natural land and desertification will help us understand the contribution of semi-natural land maintaining the stability of ecosystems. For the spatial scale analysis, we analyzed 1) the area of land desertification of different semi-natural land types at the basin scale; 2) the relationship between the area proportion of land desertification and that of semi-natural land at the sub watershed scale, as well as the area of land desertification under different combination patterns of semi-natural land types.

For the time scale, the first period, 1990–2000, represented the water-deficit conditions when the lower reaches of Tarim River fell dry and terminal lakes Lopnor and Taitema vanished. The second period, 2000–2010, was the period with improved water resource conditions because of the ecological water conveyance project implemented since 2000. Therefore, we explored the relationship between semi-natural land and land desertification in two periods under different water resource environments.

3. Results

3.1. Spatial pattern of semi-natural land in Tarim Basin

We generated maps of semi-natural land in Tarim Basin for 1990, 2000 and 2010, respectively. The resultant map in 2010 was evaluated with *in-situ* field data with an overall accuracy of 86.72%, 87.20% accuracy in the up and middle reaches and 84.67% accuracy in lower reaches.

Semi-natural land in Tarim Basin was 10.77×10^4 km² in 2010. The area proportions of desert-vegetation type, native-oasis type, artificial-oasis type, saline type, and wetland type were 59.59%, 14.65%, 11.25%, 9.63% and 4.88%, respectively. Semi-natural land types showed obvious

different spatial patterns among nine watersheds (Fig. 3). For watersheds with fragile ecosystems, such as The mainstream of Tarim River, Keriya River Basin, Qarqan River Basin, Hotan River Basin, and Kaidu-Kongque River Basin, desert-vegetation type and native-oasis type were the major types, with the total area proportion above 70%. Whereas, watersheds with advanced irrigation agriculture, such as Aksu River Basin, Weigan River Basin, Kashgar River Basin, and Yarkant River Basin, had large areas of artificial-oasis type and saline type.

3.2. Spatio-temporal dynamics of semi-natural land in Tarim Basin

From 1990 to 2010, semi-natural land in Tarim Basin decreased by 9769.05 km², dominated by the decrease of desert-vegetation type and native-oasis type, 11,943.91 km² and 1612.65 km², respectively (Fig. 4). For both periods, native-oasis type decreased, yet the decrement in the second period was 4.71 times more than that in the first period. Additionally, artificial-oasis type first decreased and then increased. The difference suggested a more substantial human modification on the environment and increasing expansion of artificial oasis in the second period.

Dynamics of semi-natural land showed remarkable differences among nine watersheds. All the watersheds experienced decrease in the total area of semi-natural land except Weigan River Basin. Kaidu-Kongque River Basin and the mainstream of Tarim River had the largest decrease with dominance of desert-vegetation type. The main difference in spatial dynamics among two periods lay in the fact that the semi-natural land in Kashgar River Basin and Weigan River Basin first increased and then decreased, whereas that in other watersheds decreased in both periods. The primary reason for Kashgar River Basin was cropland converting to desert-vegetation type resulting from sandstorm struck. Saline type increased with demands for salinity drainage by the cultivated land expansion, resulting in the increment of seminatural land in Weigan River Basin. In addition, for Hotan River Basin, Kaidu-Kongque River Basin, the mainstream of Tarim River, and Keriya River Basin, the area of semi-natural land loss in the former period was



Fig. 3. Spatial distribution map of semi-natural land in Tarim Basin in 2010. The inset histogram shows area of five types of semi-natural land among nine watersheds. The corresponding watersheds' names are presented in Fig. 1.

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Fig. 4. Dynamics of semi-natural land in nine watersheds in 1990–2000 and 2000–2010. The corresponding watersheds' names are presented in Fig. 1.

more than that in the latter period, and other watersheds were the opposite.

Conversion between semi-natural land and non-semi-natural land was analyzed at watershed scale (Fig. 5). Non-semi-natural land included artificial/semi-artificial land and natural land. In particular, artificial/ semi-artificial land in our study included cropland, built-up land and orchards. Natural land referred to unused land. From 1990 to 2010, both artificial/semi-artificial land and natural land increased in area, and semi-natural land decreased. For the fragile watersheds, semi-natural land was mainly converted to desert (>55%), demonstrating the degradation of semi-natural land. While for the watersheds characterized by advanced oasis agriculture, artificial-oasis type land was mainly converted to cropland (>54.17%), demonstrating the decrease of semi-natural land primarily resulting from the expansion of artificial oasis.

3.3. Linkages between semi-natural land and desertification

Desertification characteristics are dependent on different semi-natural land types. Fig. 6 showed that desert-vegetation type occupied the largest part of the total area of desertification of semi-natural land during 1990–2000. Over 50% of both saline type and desert-vegetation type of semi-natural land suffered desertification. These two types of semi-natural land were more prone to desertification than the other types in the background of water shortage. However, both the area and area proportion of desertification of these two types substantially decreased in 2000–2010. Additionally, native-oasis type and wetland type deceased in area of desertification. Specifically, area of desertification of artificial-oasis type increased in the second period, while the area proportion was almost unchanged, which was caused by its substantial expansion of artificial-oasis type.

Desertification is dependent on semi-natural land proportion levels at the sub watershed scale. 241 sub watersheds were categorized into 10 classes based on 10% intervals of area proportion of semi-natural land. The proportion of desertification area to total land area, expressed as a percentage, was analyzed in two periods, respectively (Fig. 7). Results showed that as the proportion of semi-natural land increased, the proportion of desertification decreased for both periods. The significance level was higher in the first period than that in the second one, which may be caused by the impact of ecological restoration of human intervention and warm-wet climatic patterns during 2000–2010. The



Fig. 5. Dynamics of semi-natural land in nine watersheds from 1990 to 2010. The corresponding watersheds' names are presented in Fig. 1.

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Fig. 6. The area of desertification of semi-natural land during the two periods.

results showed that 1) semi-natural land played a role in slowing land desertification; 2) semi-natural land had a stronger relationship with desertification under water-limiting conditions, that was, semi-natural land yielded more contribution to the alleviation for the occurrence and development of desertification under the condition of shortage of water resources; 3) furthermore, the linear equation showed that to achieve the same effect of combating desertification, more semi-natural land was required under water-limiting conditions.

Desertification is dependent on different combination patterns of semi-natural land types (Fig. 8). According to the share of different types of semi-natural land in each sub watershed, 241 sub watersheds were grouped into five classes with different dominated semi-natural land types. Statistics on area of desertification based on five classes showed that from the first to the fifth class, with the increase in area of desert-vegetation type of semi-natural land, desertification area was increasing. For the first class with the largest share of wetland type and the lowest share of desert-vegetation type, the total area of desertification was minimal. We concluded that the watersheds with desert-vegetation type dominated were prone to desertification processes. According to the watersheds dominated by artificial-oasis type or wetland type, desertification was not prone to happen.

4. Discussion

4.1. Opportunities and challenges in remote sensing of semi-natural land and desertification

Land cover information from Landsat TM/ETM + data was used for identifying semi-natural areas based on the following two facts. First, Landsat's 30-m resolution is ideal for characterizing human-scale processes and measuring human impacts on the land (NASA, 2012). Second, Landsat data works well for detecting landscape changes over time because of the consistency of Landsat dataset spanning over four decades from sensor to sensor and year to year (Markham and Helder, 2012; NASA, 2012). There were extensive human disturbances on the natural/semi-natural areas in Xinjiang, and about 6.3×10^5 ha and 11.6×10^5 ha grassland were reclaimed to cropland in northwestern China during 1990-2000 and 2000-2010, respectively, which were mainly in Xinjiang (Liu et al. 2014). Restricted by the data availability, Landsat data in *circa* 1990, 2000, and 2010 were successfully applied to track the extensive changes of semi-natural systems. Nowadays, the combination of Landsat TM/ETM + with new satellite images, e.g., Landsat 8 OLI, Sentinel-1 and Sentinel-2, will improve semi-natural landscape changes monitoring in both spatial (10 m) and temporal





Fig. 8. Area of desertification in five sub watershed classes with specific combination of semi-natural land types.

resolution (<5 days) (Drusch et al., 2012; Wulder et al., 2015). The rising cloud storage and computing, *e.g.*, Google Earth Engine (Moore and Hansen, 2011; Hansen et al., 2013), provides an important platform for processing massive volumes of satellite imagery. The increasing data availability and computing capability will perform timely landscape monitoring at 10-m resolution, which would be more sensitive to the landscape changes than that of 30-m Landsat product and will be critically needed for the landscape planning in the arid regions with fragile environment in the future work.

Limitations in the classification process mainly arise from the quality of input data. Uncertainties contained in the input data are influenced by the following: (1) various resolutions of the data sets. The 30-m NLCD product in 1990, 2000 and 2010, visually interpreted from Landsat images, was used as the baseline maps for semi-natural land classification (Liu et al. 2005a,b; Liu et al., 2014). However, it is difficult to analyze the vegetation coverage and desertification using time series Landsat images and automatic classification algorithm, as many Landsat images haven't been ingested into USGS data archive (Wulder et al., 2015) and their data availability is limited in this study area. Therefore, based on the NLCD product, 8-km GIMMS NDVI as well as 1:1,000,000 geomorphological map of Tarim Basin was included as auxiliary data to identify those semi-natural lands and desertification. MODIS products provide relatively high spatial resolution; however, the data availability is limited before 2000 (Friedl et al., 2010). Despite the relatively coarse spatial resolutions of GIMMS 3g NDVI (Guay et al., 2014), the dataset can provide the general patterns of vegetation coverage and desertification from 1990 to 2010 (Dardel et al., 2014; Zhu et al., 2012). (2) The accuracy of the data sets interpreted from remote sensing data. The overall accuracy of this 30-m land use and cover data reaches over 94% with variability in class-specific and period-specific accuracies (Zhang et al., 2014). Besides, the smallest patch and shortest edge of land use change detected are defined over 36 pixels (3.24 ha) and 4 pixels (120 m) (Liu et al., 2005a,b).

4.2. Potential reasons for semi-natural land change

Both physical conditions and anthropic activities are regarded as potential driving forces for semi-natural land change in Tarim Basin. Spatial difference of semi-natural land change among nine watersheds implies different contributors. Climate variability seems to significantly affect the evolution of the Hotan Oasis (Amuti and Luo, 2014). Located downwind of Taklimakan Desert, semi-natural land in Hotan basin is vulnerable to desertification due to the southward movement of shifting sand dunes under prevailing near-surface northeasterly winds. Physical conditions are also important drivers for the decline of 'Green Corridor' at the lower Tarim River because of the invasion of the Kuruk Desert and the Taklimakan Desert, more salt accumulation and less soil moisture (Feng et al., 2005; Huang and Pang, 2010; Wang and Cheng, 2000). The reduced glacier melting induced by climate warming will decrease the water availability in the future and further threaten natural ecosystems (Keilholz et al., 2015).

Under the background of vulnerable ecosystems, human activities are demonstrated the dominant cause of the land cover change (Liu et al., 2013). Since the late 1980s when 'warm and wet transition' occurred (Liu et al., 2006), increasing trend of precipitation, aridity index and headwater runoff formation have been detected (Tao et al., 2011). However, downstream runoff shows a negative trend due to anthropogenic influence (Sorg et al., 2012; Tao et al., 2011). That is because water discharge to the lower reaches of Tarim River has decreased rapidly (Huang and Pang, 2010) as a result of intensive human exploitation of natural resources in the upper and middle reaches of the river. Since 1972 until 2000, water has ceased to flow in the lower reaches (Tao et al., 2008), accompanied with the vanishing of lakes Lop-nor and Taitema, severe damages to the riparian vegetation and accelerating desertification (Chen, 2014; Huang and Pang, 2010; Thevs, 2011; Zhang et al., 2010). Since 2000, significant positive effects of the ecological water conveyance project have been demonstrated (Aishan et al., 2015; Chen et al., 2010; Ye et al., 2009b).

4.3. Potential reasons for different relationships between semi-natural land and desertification in two periods

The Xinjiang Tarim River Basin water unit annual total water use quota (for Trial Implementation) was approved in 1999 to ensure the reasonable water allocation among different ecosystems, especially for natural ecosystems. Since the Tarim River recent integrated management project was carried out in 2001, a series of measures have been taken to increase species diversity by replanting species such as *Tamarix chinensis*, flooding irrigation and improving the water use efficiency of natural vegetation. For example, in Kaerdayi section, the dominated vegetation communities were shifted from sparse herbaceous species to shrub and herbaceous species, which could improve the ability of resistance to desertification.

Taking the lower reaches of Tarim River for example, ecological water conveyance project may be an important potential reason. The change of groundwater depth of four typical sections in the lower reaches of Tarim River was monitored before and after the project (Fig. 9). Before 2000, groundwater depth of the four study sites was



Fig. 9. Changes in average annual groundwater levels for typical sections in the lower reaches of Tarim River.

below the groundwater threshold of desert riparian vegetation (6 m; Hao and Li, 2010). The groundwater depth of four sections has risen up around the threshold groundwater level since the implement of the project, which was favorable for recovery of riparian vegetation and prevention of desertification.

4.4. Policy implications

The reasons for the substantial decrease in semi-natural land included conversion to artificial/semi-artificial land because of population growth and economic development and conversion to desert because of desertification of semi-natural land. Correspondingly, on one side, the reasonable proportion of semi-natural land should be preserved by prohibited clearance for artificial oasis through policy intervention. In specific, more semi-natural land should be preserved especially in water-limiting watersheds and periods, and semi-natural land types with high vegetation coverage should be preferred to. On the other side, rational allocation of water resources should be performed to satisfy the water demand among different ecosystems to avoid the degradation of semi-natural land.

5. Conclusions

In this study, we established a semi-natural land classification system, developed an approach for mapping semi-natural land using multi-source datasets at large scales and analyzed the spatio-temporal dynamics of semi-natural land in Tarim Basin. We also determined the desertification based on remote sensing data. Then the relationships between semi-natural land and desertification at the sub watershed scale were demonstrated in two periods (1990–2000 and 2000–2010). This study will provide reference for future research on semi-natural land in arid regions and spatial implications for formulating development strategies and ensuring regional ecological security.

The quantitative relationship between semi-natural land and desertification was demonstrated in our study. Semi-natural land has decreased by 9769.05 km² since 1990. The substantial loss of seminatural land will lead to serious implications on ecological security and sustainability development of human society. Therefore, there is an urgent need for locals to prevent degradation and shrinkage of semi-natural land and preserve reasonable area to alleviate the desertification process. Furthermore, reasonable area of semi-natural land required for oasis stability and ecological security vary with different water resource conditions, which should be considered in the future optimized allocation for landscape planning.

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